I. LONG-BASELINE PHYSICS

A. ν_e Appearance

1. *LBNE Beam Design and Physics Sensitivities*

The LBNE beamline is a new neutrino beamline to be built at Fermilab that utilizes the Main Injector (MI) 120 GeV proton accelerator. The longest baseline neutrino oscillation experiment currently in operation is the Main Injector Neutrino Oscillation Search (MINOS) experiment based at Fermilab which utilizes the NuMI (Neutrinos at the Main Injector) [3] beam-line from the MI. The NuMI beam-line has been operational since Jan 21, 2005 and has delivered in excess of 1×10^{21} protons-on-target (POT) to the MINOS experiment by 2010 [4]. The GEANT [5] based simulation of the NuMI beam-line has now been validated using real data from the MINOS experiment. The NuMI simulation software has proven to be a remarkable success at predicting the measured neutrino charged-current (CC) interaction rates observed in the MINOS near detector. The level of agreement between the data and simulation CC interaction rates is within 10% in the region of interest for the MINOS experiment.

The design specifications of the LBNE neutrino beamline is driven by the physics of $\nu_\mu \rightarrow \nu_\mu$, and $\nu_\mu \rightarrow \nu_e/\nu_{tau}$ oscillations. In Figure 1, the $\nu_\mu \rightarrow \nu_e$ oscillation probability for the LBNE to DUSEL baseline of 1300km for different mixing parameters is shown as colored curves. The CC ν_μ spectrum from the NuMI beam (left) and an LBNE candidate beam (right) are shown as black solid histograms. In principle, the ideal LBNE neutrino beam would be one that has a wide energy band that coversthe energy region from low energies to the energy of the first ($\pi/2$) oscillation maximum and minimal flux beyond the region of interest. Low flux at high neutrino energies is desired to eliminate neutral-current backgrounds from high energy neutrinos that are not sensitive to oscillations but still produce significant background at low observed energies in the neutrino detectors.

In 2008/2009 we specified the following broad requirements for the LBNE beam based on examination of the oscillation nodes in Figure 1:

1. We require the maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes, the maxima of which occur at 2.4 and 0.8 GeV respectively.

2. Since neutrino cross-sections scale with energy, larger fluxes at lower energies are desirable to achieve the physics sensitivities using effects at the 2nd oscillation node and beyond.

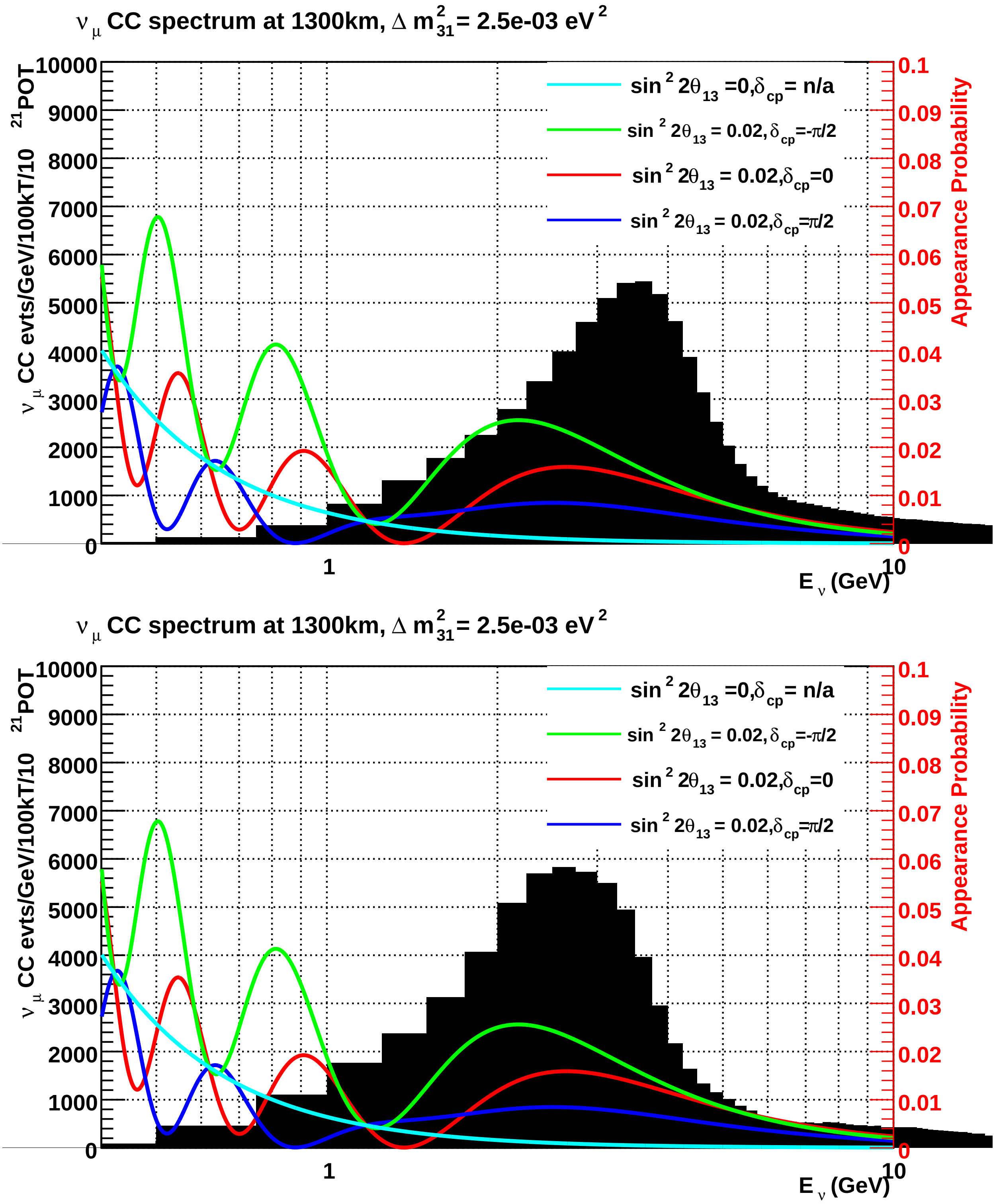

FIG. 1: The $\nu_\mu \to \nu_e$ oscillation probability for the LBNE to DUSEL baseline of 1300km for different mixing parameters is shown as colored curves. The CC ν_μ spectrum from the NuMI beam (top) and an LBNE candidate beam (bottom) are shown as solid black histograms.

3. To detect $\nu_\mu \to \nu_e$ events at the far detector, it is critical to minimize the neutral-current contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is little sensitivity to the oscillation parameters (including the CP phase and the mass hierarchy) is highly desirable.

4. The irreducible background to $\nu_\mu \to \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity ν_μ beam with as low as possible ν_e contamination is required.

For 2010, we propose refining the physics requirements of the beam to include the impact of the beam designs on the *resolution* of the value of $sin^2 2\theta_{13}$ and δ_{cp}.

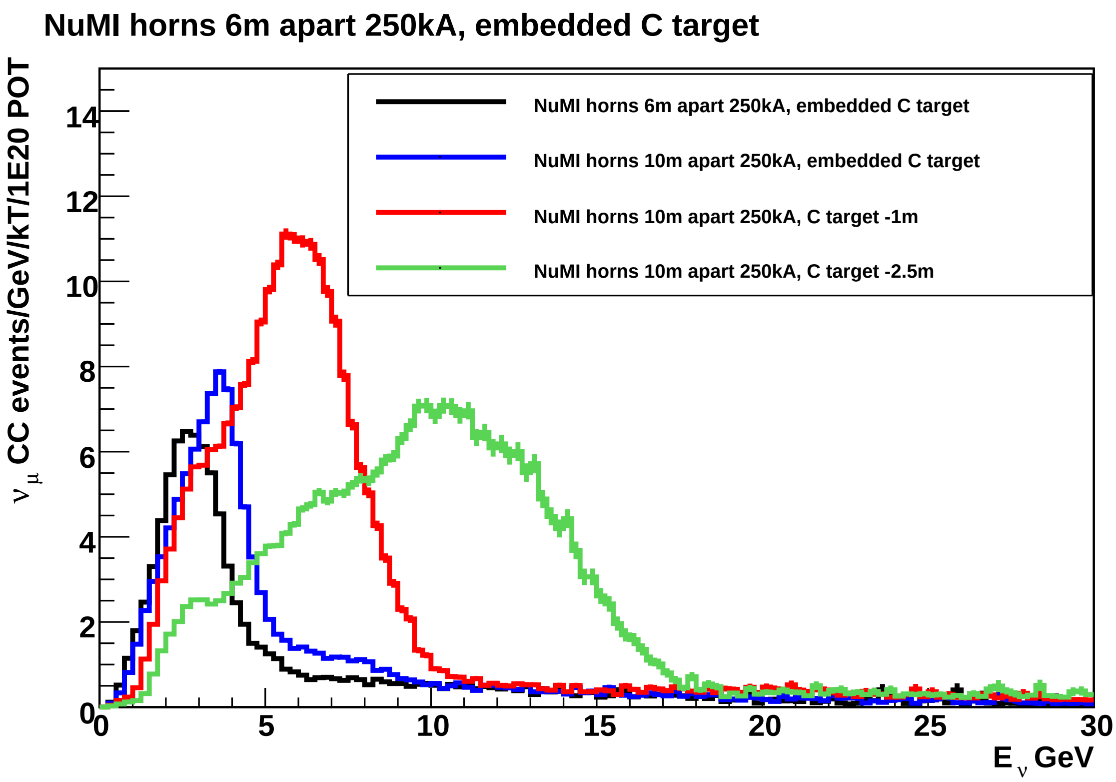

FIG. 2: Various ν_μ CC spectra obtained using variations on the NuMI based LBNE design. In this design, both focusing horns are identical to NuMI. The target is a carbon target with density = 2.1 g/cm^3 and radius = 0.6cm, and length 80cm. The decay pipe is 2m in radius and 280m in length and is evacuated. Changing the horn current, and the target and horn configurations can be used to obtain a highly tunable beam spectrum.

CONCLUSION: The CDR design and the 2009 reference design have similar resolution of δ_{cp} and $\sin^2 2\theta_{13}$. The 2009 reference beam design with either a 350kA current and embedded target OR a 250kA with the target -0.5m from the face of horn 1 gives us significantly improved resolution

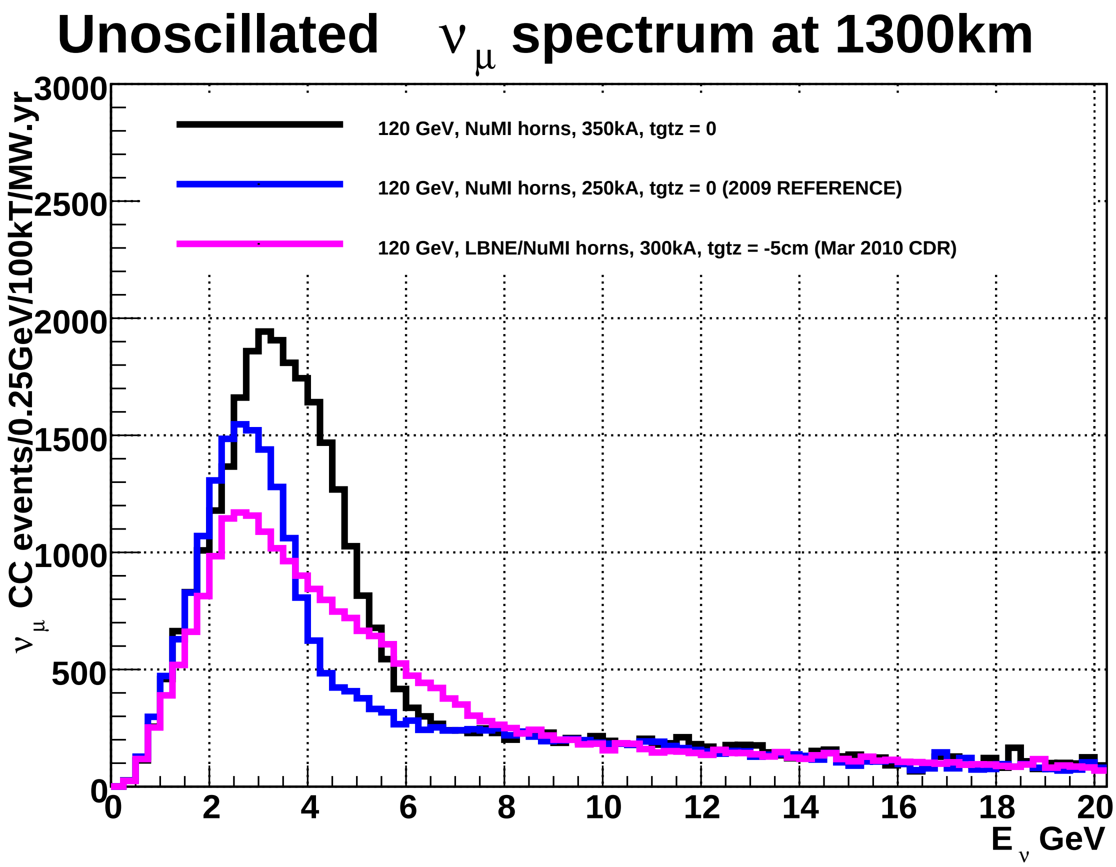

FIG. 3: The unoscillated ν_μ CC spectra at the far detector obtained using different LBNE designs. The blue and black spectra were obtained using the NuMI based LBNE design described in Figure 2. The design with the highest horn current (black) currently gives us the best resolution on δ_{cp} and $\sin^2 2\theta_{13}$. In magenta the March 2010 version of the design described in the CDR is shown. In the CDR a different lower density larger carbon target is used, a modified Horn 1 is used along with NuMI horn 2. The decay pipe is slightly shorter at 250m and is filled with air at STP. The shape of the upstream end of horn 1 and the air in the decay pipe are the most significant changes from the 2009 reference design (blue curve).

of δ_{cp} and $\sin^2 2\theta_{13}$ as compared to the CDR design or the 2009 reference design. Its not yet clear whether the improvement will presist when detector effects are included. The option of using the parabolic NuMI horns with 250kA and a target moved further back is technically more feasible than running the NuMI horns at 350kA with a fully embedded target. We hope the beamline technical design group will SERIOUSLY consider this option. All beams currently studied do not have sufficient flux at the second maxima to impact the measurement of δ_{cp} and $\sin^2 2\theta_{13}$. Preliminary estimates indicate that we would require at least 5X more flux at the 2nd maxima to significantly improve the measurement of δ_{cp} and $\sin^2 2\theta_{13}$.

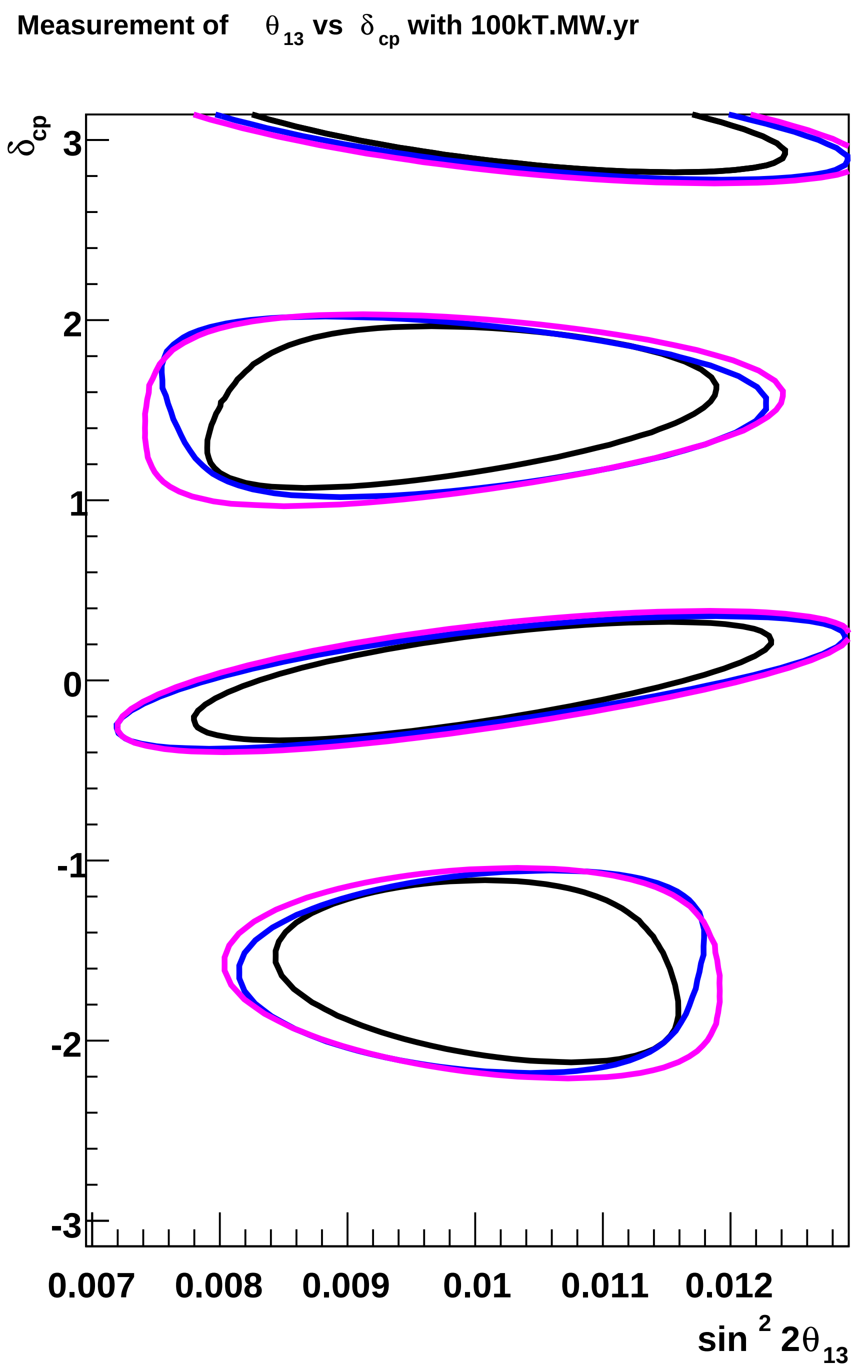

FIG. 4: The 1σ measurement contours of δ_{cp} vs $\sin^2 2\theta_{13}$ for normal hierarchy obtained from the beams described in Figure 3. There are no detector effects. The only background is the intrinsic nu_e contamination in the beam.

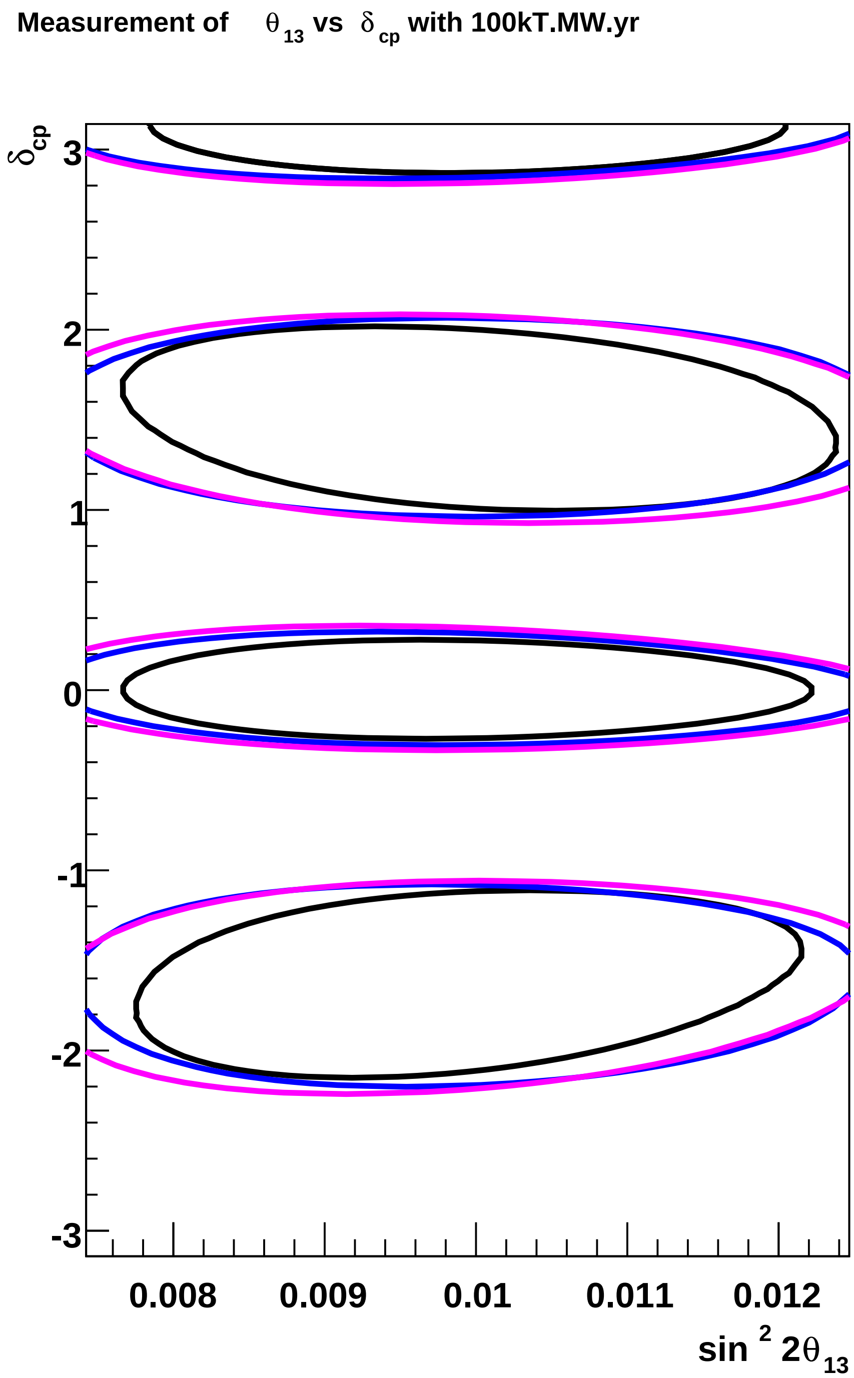

FIG. 5: The 1σ measuremnt contours of δ_{cp} vs $\sin^2 2\theta_{13}$ for inverted hierarchy obtained from the beams described in Figure 3.

B. ν_μ Disappearance

C. Conclusions

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[2] B. Rebel, private communication.

[3] J. Hylen *et. al.*." Conceptual design for the technical components of the neutrino beam for the main injector (NuMI).", FERMILAB-TM-2018 Sep (1997).

[4] D. G. Michael *et. al.* "Observation of muon neutrino disappearance with the MINOS detectors in the NuMI neutrino beam". hep-ex 0607088, FERMILAB-PUB-06-243, BNL-76806-2006-J A.

[5] R. Brun *et al.*, CERN-DD-78-2-REV

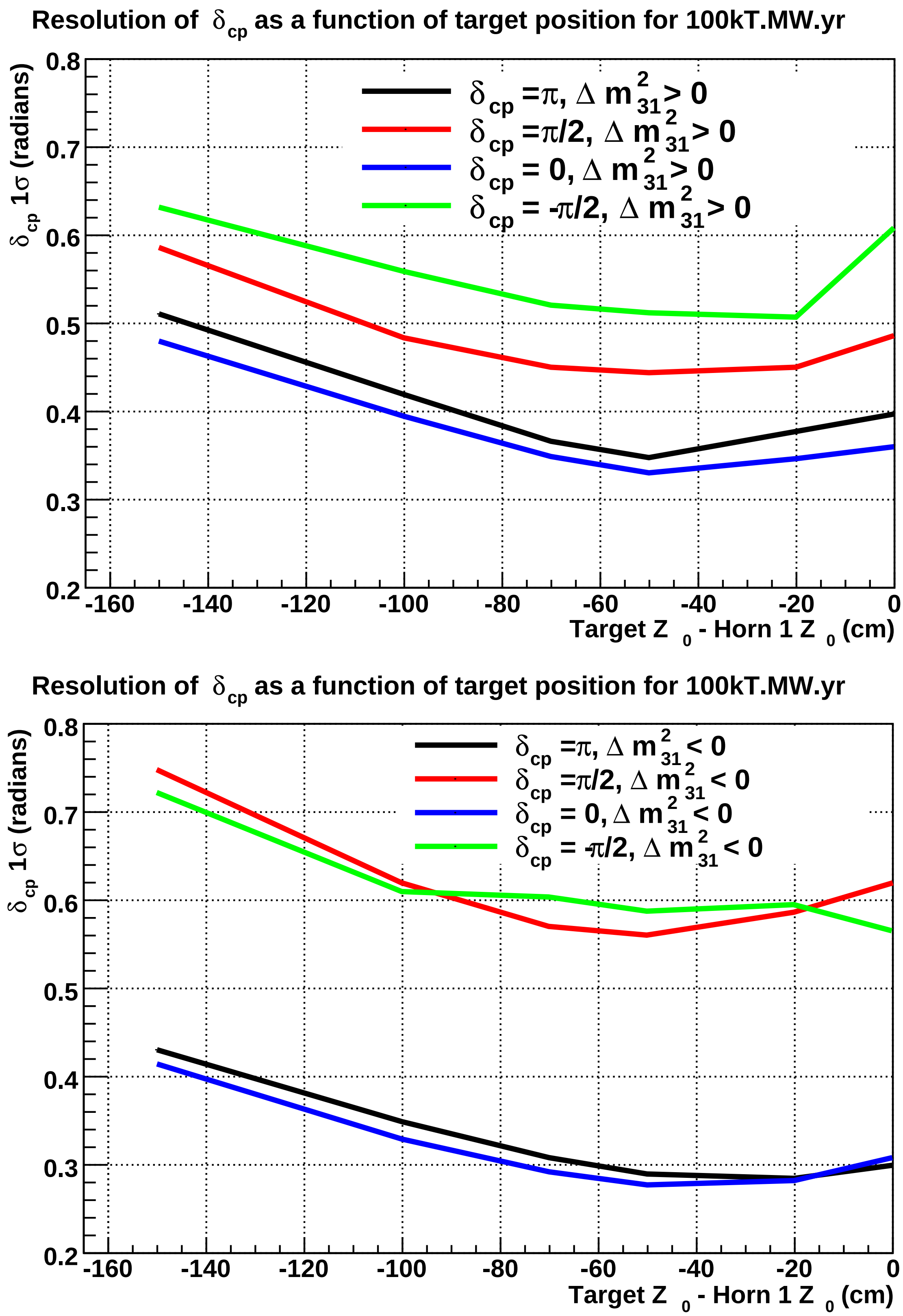
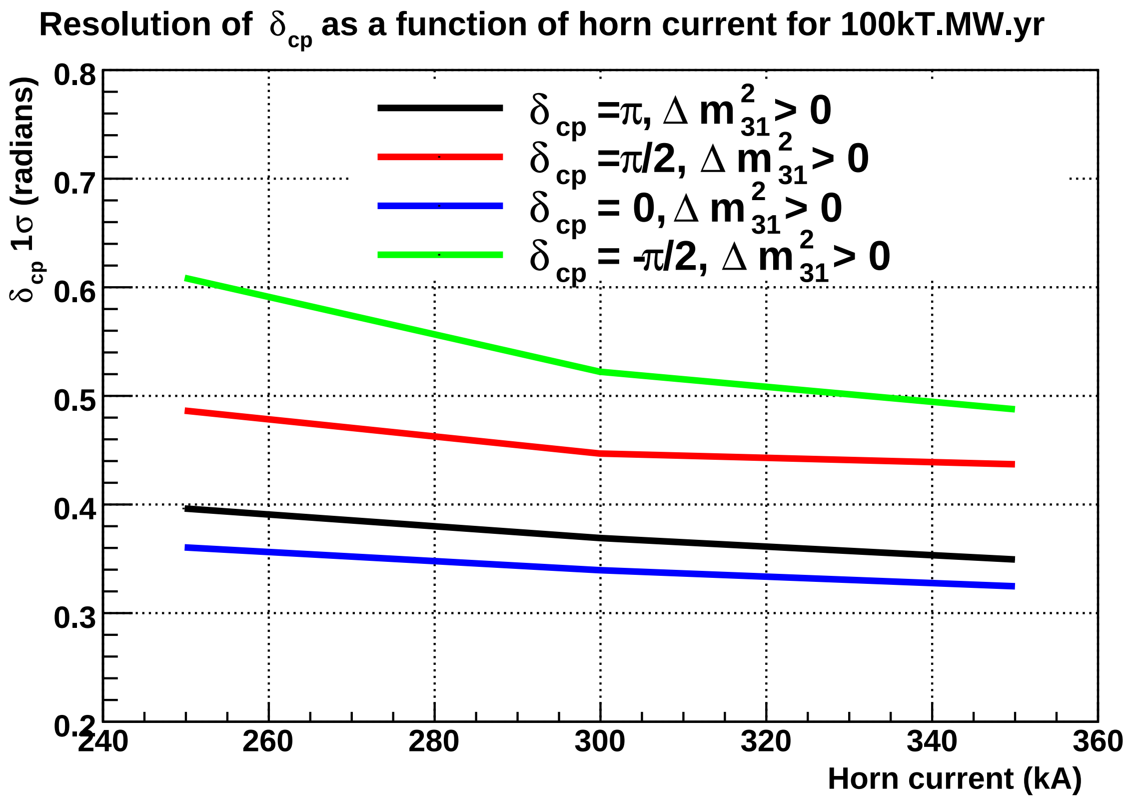


FIG. 6: The 1σ resolution of δ_{cp} as the target position is changed in the 2009 LBNE beam design. Normal hierarchy (top) and inverted hierarchy (bottom).



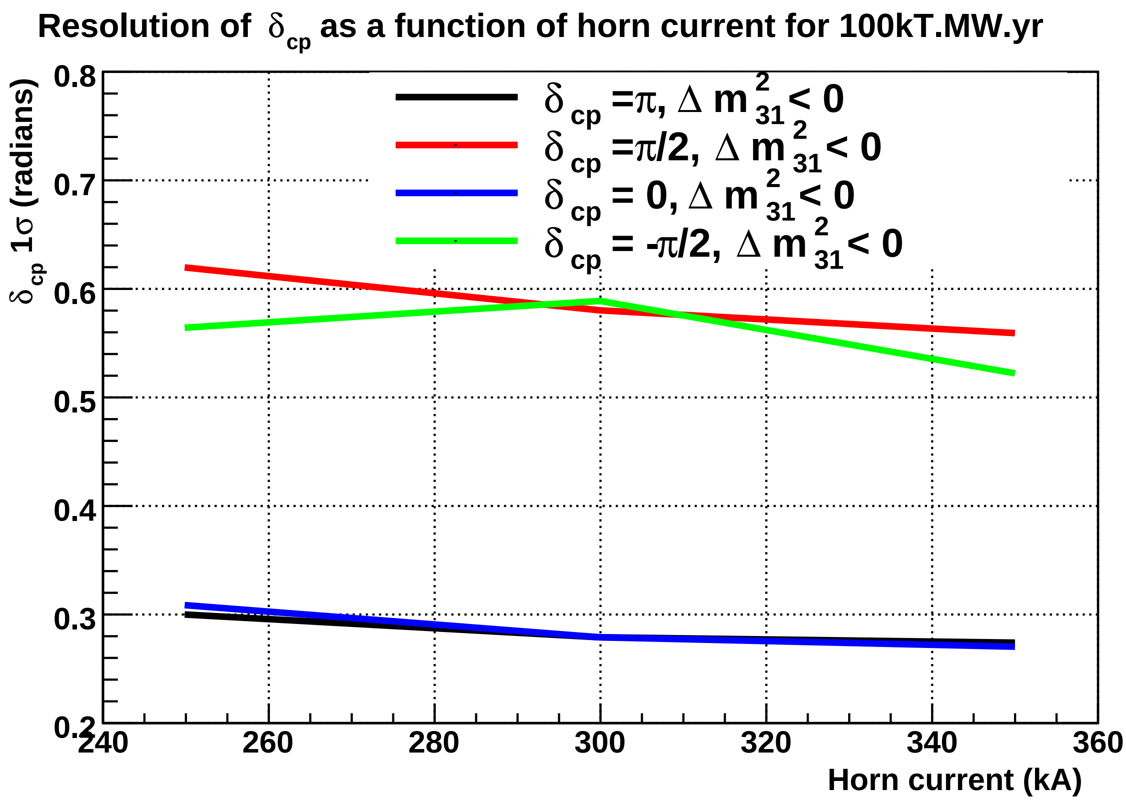


FIG. 7: The 1σ resolution of δ_{cp} as the horn current is changed in the 2009 LBNE beam design. Normal hierarchy (top) and inverted hierarchy (bottom).